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A. TITLE:

Vector-Meson Decay of High-Lying Nucleon Resonances

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C. THIS PROPOSAL IS BASED ON A PREVIOUSLY SUBMITTED LETTER OF INTENT

[XX] YES
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Neutral Rho Photoproduction on Hydrogen and Deuterium Targets

D. ATTACH A SEPARATE PAGE LISTING ALL COLLABORATION MEMBERS AND THEIR INSTITUTIONS

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Vector-Meson Decay of High-Lying Nucleon Resonances

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ABSTRACT

Vector-meson decay of baryon N^* and Δ resonances will be studied through photoproduction reactions as a means of identifying new but predicted resonances and for making critical tests of quark models inspired by QCD. Several quark models can successfully describe the known baryon resonances up to masses of about 2000 MeV. These models also predict the existence of other resonances that are as yet unidentified. Several of the resonances have appreciable couplings to the γN, ρN, and ωN channels, and they may have been unpopulated in earlier πN experiments. The Isgur-Karl model, the Quark-Pair-Creation model, and other models predict substantial omega decay widths of many of the baryon resonances, but there are as yet no data for this decay mode. The proposed experiment will use a 2.4-GeV electron beam and the photon tagger to produce photons over the energy range of 700–2150 MeV, corresponding to the s-channel resonance mass range of 1500-2200 MeV. Vector mesons will be detected in the CLAS detector, which will also be modified to permit the detection of π^0 particles from the decays of $\rho^\pm$ and ω mesons.

1 Motivation

Meson photoproduction is a old subject with extensive studies dating back to the 1960's when many new accelerator facilities were commissioned. The simplest process is single-pion production, for which there is quite substantial data. However, the subject that has probably received the greatest attention over the years is the production of vector mesons, which are typically identified through their decays into multipion final states. Much of the work on this subject culminated in the discovery of the charmed J/ψ vector meson, which opened up new research opportunities and initiatives.

Nevertheless, in spite of considerable data and broad understandings, much remains to be learned about conventional meson photoproduction. The earlier experimental work was never really completed and, in the meantime, a number of quark-based models were developed. Calculations based on these models provide detailed descriptions of hadron spectroscopy and interactions. These models take their inspiration from the discovery of the J/ψ and subsequent studies, and by the advancement of QCD as the fundamental theory of hadronic interactions.[1] Examples of such theoretical models include the Quark-Pair-Creation model (QPCM),[2] and the Isgur-Karl model (IK).[3,4,5] Vital tests of these models include the photoproduction of baryon resonances and identification of their mesonic decay channels.

As a result of previous work, there is already considerable understanding of the dominant photoproduction mechanisms, and many review papers have been written on the subject.[6,7,8,9,10,11,12] For photons of a few hundred MeV energy, single-pion production is the principal mode, resulting from excitation of the $\Delta(1236)$ as an s-channel resonance. Two-pion production has a sharp onset near 600 MeV photon energy. Rho production is kinematically allowed above 1.1 GeV; for the next several hundred MeV, many of the rhos appear to arise from the decay of N^* and Δ resonances.

At photon energies greater than several GeV, a diffraction mechanism becomes dominant. This process is defined as that in which there is no change in the quantum numbers of the interacting objects, such as isospin, G-parity, and spin-parity series.[10] The cross sections change smoothly with energy and are roughly proportional to elastic hadron (*e.g.*, pion) scattering with a 4-momentum-transfer t dependence that is approximately exponential. The process is also characterized better with natural-parity-exchange amplitudes in the t channel, rather than by s-channel resonances. Photons, having intrinsic spin-parity 1^- and a mixture of isovector and isoscalar amplitudes, may thus be understood as having a hadronic component that is manifested as a conversion into a vector ρ, ω, or ϕ meson which then scatters peripherally from a nucleon. At even higher energies, particularly above 10 GeV, the large-t behavior of photons increasingly shows characteristics of point-like interactions with quarks.[12]

Data on non-diffractive mechanisms are relatively sparse and generally poor in quality. In particular, there are almost no useful data on the photoproduction and meson decay of nucleon resonances above about 1600 MeV. On the other hand, good data exist on pion elastic-scattering and $(\pi, 2\pi)$ reactions up to about 2 GeV center-of-mass energy. They have been embedded in many phase-shift analyses,[13,14,15] the most recent and extensive one coming from the VPI group.[16] Photoproduction reactions provide an independent means of producing the resonances, including new resonances, and the fact that the photons can be polarized makes possible the measurement of other experimental observables that can be used to constrain future analyses.

CEBAF will be an ideal laboratory for new physics since the available energies perfectly span the transition between regions dominated by resonance and diffraction processes. The high intensity of the photon beams, the unprecedented resolution of the photon tagger, and the outstanding features of the nearly 4π CLAS detector will enable experiments of unparalleled quality. Weaker components in the production processes can be explored in detail, with the results leading to important new understandings in hadronic interactions.

We propose to initiate a program in meson photoproduction that will produce data of very high quality and, from those, will address entirely new issues. The initial emphasis will be on the production of vector mesons from nucleons in the center-of-mass energy range that corresponds to baryon masses between 1500 and 2200 MeV, especially as it arises from the decay of known and as yet unknown baryon resonances. Specific predictions[4,5] of rho and omega decays of baryon resonances in the model of Isgur and Karl[3] will be tested. Since no omega decays of resonances have as yet been identified, this experiment will provide a unique opportunity for significantly new physics. Efforts will be made to separate non-diffractive from diffractive processes by looking at charge-exchange channels where appropriate, and by obtaining data at large t ($-t > 1$ (GeV/c)^2). Evidence will also be sought for the production of other mesons, including the phi meson as well as both strange and non-strange scalar mesons. Subsequent experiments will provide essential new data with polarized photons, and will extend studies to heavier nuclei.

2 Summary of Previous Work

The literature of meson photoproduction, particularly vector meson production, is extensive and we shall not attempt to review it here. Several review articles were noted in Sect. 1, and references to the many experimental and theoretical papers may be found therein. We shall, however, provide a broad overview of the subject so that the present proposal can be viewed in proper perspective.

The earliest complete experiments in single- and multipion-photoproduction reactions were those at 6 GeV of the Cambridge Bubble Chamber Group at the CEA,[17] and those at 5.8 GeV of the ABBHHM collaboration working at DESY.[18] Separate papers were written that concentrated on rho,[19] omega,[20] and phi[21,22] production. These were all unpolarized-bremsstrahlung and bubble-chamber experiments. Soon after, more detailed studies were carried out with roughly monochromatic and polarized photon beams of 2.8 and 4.7 (and eventually 7.5) GeV at SLAC.[23] There was extensive work during the 1970's at Cornell and at the NINA electron synchrotron in Daresbury, as well as additional work at SLAC.

The essential features of these reactions can be summarized as follows. For invariant masses $M_{\pi\pi} < 1$ GeV, 60-80% of the total $\pi\pi$ cross section from hydroden is due to ρ^0 production. At energies above 2 GeV or so, the production mechanism is more than 90% diffractive. The ρ^0's are produced with transverse polarization, like the photon, with s-channel helicity conservation. Natural-parity exchange dominates in the t channel, consistent with a roughly 10% non-diffractive one-pion-exchange (OPE) contribution. Although the cross sections are much smaller, and the experimental statistics much poorer, similar remarks apply to ω and ϕ production as well.

In the case of deuterium, the total cross section for ρ^0 production with a deuteron in the final state is much larger than that in which the deuteron is broken up and there is a spectator proton or neutron in the final state. Again, the production is dominantly diffractive with s-channel helicity conservation and t-channel natural-parity exchange. The ratio of isovector to isoscalar production amplitudes is estimated to be 10-15%;[24,25] the isovector amplitude is believed to arise from ρ and A_2 exchange.

Information on non-diffractive processes is at best spotty.[26,27,28,29,30,31] Thus, in the diffractive region, the total cross section for $\rho^-\Delta^{++}$ photoproduction on hydrogen is about 1/10 of that for ρ^0 production; the $\rho^+\Delta^0$ channel is nearly absent. On the basis of polarized-photon experiments, natural- and unnatural-parity exchange amplitudes for non-diffractive processes appear to be comparable. The subject is ripe for additional experimental studies.

3 Hadronic Interactions and Quark Models

Descriptions of hadron-hadron interactions at low and medium energies, such as those that will prevail at CEBAF and which are dominant in nuclei, are commonly based on the use of meson-baryon coupling constants. Examples include the couplings at πNN, ρNN, ρNΔ, ωNN*, *etc.*, vertices. To the extent that they characterize the interactions among the elementary particles, they are of fundamental significance. For nuclear physicists, the effective modification of the coupling constants by the nuclear medium becomes a means of learning about the collective properties and polarizing effects of that many-body system.

Pion beams have been available for many years, especially at the "pion factories", and much is known about the πNN and πNΔ vertices. Because reasonable beams of heavier mesons do not exist, the information available for the corresponding vertices with heavier mesons is much more limited and not entirely consistent. For example, tabulations of the vector and tensor ρNN coupling constants show a range of a factor of two or more,[32] and show substantially greater ranges for the ω and ϕ mesons.

Underlying the meson-baryon descriptions of strong interactions, however, are descriptions based upon their quark constituents. QCD is widely acknowledged as being the fundamental theory for all hadronic interactions, although it has not yet been developed quantitatively to the level needed to describe or predict experimental data. Instead, several models based on quarks and gluons, many of them with ingredients inspired by the elements of QCD, have been developed. These models give predictions for the spectroscopy of mesons and baryons including the energies of the states, their quantum numbers, and their decay widths into various channels. Even though the models do not accurately reflect the full scope and power of QCD, they serve as conceptual frameworks for practical treatments of hadronic interactions. As such, they need to be tested and refined. For purposes of the present discussion, the two quark-based models to be considered are the "naive" Quark-Pair-Creation model[2] and the Isgur-Karl model.[3]

3.1 Quark-Pair-Creation model

In the case of the QPCM, an operator is introduced that explicitly creates a $q\bar{q}$ pair from the hadronic vacuum ($J^{PC} = 0^{++}$), the quarks then combining separately with the other (spectator) quarks from the hadron to form a new hadron and a meson. Symmetries require that the $q\bar{q}$ pair be created in a $^3P_0$ configuration. In contrast with the methods used in earlier such models, the internal momenta of the quarks are taken into account and the creation matrix elements are evaluated in terms of harmonic-oscillator wave functions. Polarization effects are successfully described through a "recoil" term that arises naturally in the model. However, there is one undetermined overall constant in the model and the hadrons at a vertex are treated nonrelativistically.[2]

3.2 Isgur-Karl model

The Isgur-Karl model[3] is a nonrelativistic quark model in which baryons are treated as bound states of three "constituent" quarks subject to a color hyperfine interaction, as suggested by QCD. The confining potential is flavor independent and is approximated by a harmonic-oscillator potential that is perturbed by an arbitrary anharmonic term. The up and down quarks are given the same mass but the strange quark is more massive, thus breaking SU(3) symmetry. The spin-dependent interactions produce mixing among the SU(6) group-theoretic classification of the states, in contrast with the results of the QPCM and other older models. Meson emission from baryon resonances is accomplished through an elementary effective interaction for $q \to qM$.

The negative-parity baryons form a multiplet with total orbital angular momentum $L = 1$. A good description of the energies is provided for known N^* and Δ states up through 1700 MeV mass, as shown in Fig. 1; the model space is not large enough to provide states above that energy. Spectra for the positive-parity excited N^* and Δ baryons are shown in Fig. 2. The experimental spectra include possible resonances designated with only one or two stars by the Particle Data Group[33] as well as some resonances that are possibly observed in the VPI phase-shift analysis of πN data.[16] Correspondence between the empirical and the model spectra is very cloudy above about 1800-MeV mass, with many of the model N^* states not having identified experimental counterparts.

3.3 Decays of baryon resonances

Considerable information about the decays of baryon resonances is already known from pion-nucleon scattering and $(\pi, 2\pi)$ reactions. The data have been incorporated into various phase-shift analyses from which have emerged the identification of resonances and their decays.[13,14,15,16] As noted above, not all of the predicted positive-parity resonances are observed. There are also some discrepancies between the signs of the decay amplitudes as derived from the scattering data and from the model predictions, although the IK model seems to be slightly better than the QPCM.[16]

The photoproduction amplitudes and the π and ρ decay amplitudes for the negative-parity baryons are, for the most part, well described by the IK model,[4,5] the principle exception being the $1/2^- S_{11}$ resonance at 1535 MeV. However, there are numerous significant discrepancies between theoretical and experimental photoproduction amplitudes for the positive-parity baryons, although the πN decay amplitudes are in reasonable accord.[4]

Isgur has argued that the unobserved positive-parity resonances may not be missing, but rather that they decouple from the πN channel with several of them having good couplings to the γN channel instead.[34] A list of the photoproduction and strong-coupling amplitudes for these resonances is provided in Table I.[4,5,34] The πN decay amplitudes for these states are substantially less than the values of 6–10 that are typical for most of the other resonances, while many of them have large photoproduction and vector-meson-decay amplitudes. Thus, in order to help form a complete picture of the spectrum of baryons and their decays, it is necessary to make new studies of meson photoproduction in the resonance regions.

4 Proposed Experiment

We propose new measurements of the production of vector mesons from nucleons by use of tagged photon beams and the CLAS 4π detector at CEBAF. As the initial stage of a long-term and multifaceted program, we propose specifically to use a 2.4-GeV electron beam and the photon tagger to produce photons over the energy range of about 0.70 to 2.15 GeV with an energy resolution (segmentation) in the tagger of better than 7 MeV. These photon energies on nucleon targets correspond to total squared center-of-mass energies s = 2.2–4.9 GeV^2, or baryon resonance masses M = 1480–2220 GeV. The experiment will be done in two parts. The first part will investigate the ρ^0 decays of high-lying nucleon resonances. Following a slight modification fo the CLAS detector, the second part will study ω and $\rho^{\pm}$ decays of the resonances. Both parts will use unpolarized photons and they are also excellent choices for being among the earliest experiments with the CLAS detector. Studies of spin observables with polarized photons, which are more complex and demanding experiments, will be proposed later.

The vector mesons are known to decay predominantly into the following channels:

$$\begin{array}{llll} \rho & \rightarrow & \pi\pi & 100.0\% \\ \omega & \rightarrow & \pi^+\pi^-\pi^0 & 89.3\% \\ & \rightarrow & \pi^0\gamma & 8.0\% \\ \phi & \rightarrow & K^+K^- & 49.5\% \\ & \rightarrow & K_L K_S & 34.4\% \\ & \rightarrow & \rho\pi & 12.9\% \end{array}$$

The simplest decay mode is thus that of $\rho^0 \rightarrow \pi^+\pi^-$, since most of the others have at least one neutral particle, usually a π^0. (If the K^+ and K^- are not detected directly, their predominant hadronic decays include π^0's.)

Rho meson production from nucleons proceeds as follows:

$$\begin{array}{lllll} \gamma p & \rightarrow & \rho^0 p & \rightarrow & \pi^+\pi^- p \\ & \rightarrow & \rho^+ n & \rightarrow & \pi^+\pi^0 n \\ \gamma n & \rightarrow & \rho^0 n & \rightarrow & \pi^+\pi^- n \\ & \rightarrow & \rho^- p & \rightarrow & \pi^-\pi^0 p \end{array}$$

Note that the neutral decay channel $\pi^0\pi^0$ does not occur for ρ^0's (as dictated by isospin Clebsch-Gordan coefficients).

For a hydrogen target, ρ^0 production can be unambiguously identified, within the resolution limits of the photon tagging system, by detecting the π^+ and π^-. Detection of the recoil proton is not essential, although it will help to remove backgrounds. However, ρ^+ production produces two neutral particles and can only be identified cleanly if one of them, preferably a π^0, is detected.

Reactions on the neutron can best be done with a deuterium target. It would appear from the above list that both ρ^0 and ρ^- production can be unambiguously detected (within the limits of resolution) since there is only one neutral particle in the decay channel. However, one must also distinguish reactions on a neutron from coherent reactions on deuterium, and thus a signal for the spectator proton is also needed. The inner vertex detector of the CLAS will provide such a signal. Once again, ρ^0 production is easier to detect since it leaves only one neutral particle in the final channel.

Decay partial widths have been computed for the baryon resonances obtained in the Isgur-Karl model.[4,5] A list of the partial widths for many of the channels, and the total width, is provided in Table I. It is seen that the ρN and ωN decay widths are frequently larger than the πN widths. There is as yet no information on ω decays of the baryon resonances. We view their identification to be an important part of our proposal. The experiment will therefore provide a first-of-a-kind test of a leading quark-based model of hadronic interactions. We also aim to obtain good data for $\rho^{\pm}$ decays in order to help separate ρ decay of baryon resonances from diffractive mechanisms.

The dominance of the diffractive mechanism in the total vector-meson production cross section makes studies of the large-t region of photoproduction, in which the cross sections become small, quite difficult. The low cross sections severly inhibited the studies of this region in bubble chamber experiments, in which the luminosity was sharply limited, and in multi-spectrometer experiments where the solid angle acceptance was inadequate. The CLAS, with its nearly 4π acceptance and its ability to handle high data rates, is the ideal device for investigating the large-t region.

4.1 Experimental method

The experiment will be separated into two parts. In the first part, we will use the photon tagger and the CLAS with its inner vertex detector to study $\rho^0 \rightarrow \pi^+\pi^-$ production primarily as arising from ρ^0 decay of nucleon resonances. We propose to use liquid LH_2 and LD_2 targets with thicknesses of approximately 1 gm/cm^2 (about 14 cm long). In addition, solid CH_2 and CD_2 targets with thicknesses of 1 gm/cm^2 or less are needed in order to establish cross links between our data with the liquid targets and data from solid nuclear targets, proposed separately. Since the solid targets are more compact and since recoil protons will get out of them more easily than from the liquid targets, comparison of data with the two types of targets will give valuable information on the performance of the inner vertex detector.

The electron beam energy will be 2.4 GeV, and we expect to tag photons at the rate of 10^7/sec over the full energy range. The majority of γN reactions for our energies involve the production of ρ^0's. Thus we will use a very open trigger consisting of two charged particles in the CLAS scintillators in coincidence with the tagger. By making use of suitable time-of-flight information, we should be able to separate pions from kaons and distinguish ϕ production as well.

The second part of the experiment will involve a simple modification of the CLAS system to enable detection of omega and charged rho mesons. The presence of the π^0 in the 2-body decay of the $\rho^\pm$ or the 3-body decay of the ω will require the addition of π^0 detection capability to the CLAS. The π^0's decay via $\pi^0 \rightarrow 2\gamma$ so that double photon detection is needed. The basic method is also being suggested as part of a separate proposal to measure the total photon hadronic cross section on nuclei: thin (0.25 radiation length = 1.4 mm) lead sheets will be located between the first and second drift-chamber superlayers in the CLAS. The lead will convert photons with an efficiency of approximately 20%, leading to a π^0 detection efficiency of about 4%. Although this efficiency seems small, the product of the efficiency and solid angle nevertheless substantially exceeds that of any other known π^0 detection system of comparable energy resolution.

The electrons resulting from the conversion process will have their momenta, directions, and conversion positions measured by the outer chambers. The original photoproduction vertex can be reconstructed from the tracks of the two charged pions in the inner chamber. With the accurate information on vertex and conversion position, the 2-photon opening angle of the π^0 can be accurately determined. Combination of the opening angle with the reasonable energy resolution on the conversion electrons will give excellent π^0 energy resolution.

The presence of the converter planes will, however, degrade the momentum resolution of the charged pions since the vertex detector and inner chambers can no longer be used together with the magnetic field data to fit the momenta, except possibly in a more complicated fit in which the multiple scattering angle in the converter is included as a parameter. We estimate that the net effect will be no worse than to degrade the momentum resolution similarly to the difference between the "vertex known" and no "vertex" curves in Figure G-4 of the Hall B PCDR. From those curves, and the scaling of the field integral with the angle given by Figure F1-3 of the PCDR, we have performed a Monte Carlo calculation of the ω mass resolution. We assume forward-produced ω's which decay isotropically in their center-of-mass system. Some results are shown in Fig. 3. In each case, the contribution of the π^0 momentum resolution is neglected because it is expected to be smaller than that for the charged pions. Even up to ω momenta of 1.5 GeV, the ω mass resolution is less than 30 MeV/c^2, making the particle easily resolvable from the continuum.

4.2 Event simulation

The photoproduction of ρ^0 mesons on a proton target and its subsequent decay into $\pi^+\pi^-$ in the CLAS has been simulated through a number of Monte Carlo calculations. This work is still in progress and will be thoroughly refined prior to the experiment. Representative calculations have been made at a photon energy of 1600 MeV, corresponding to a baryon mass of about 1970 MeV.

The broad ρ^0 mass distribution is described by a Breit-Wigner shape. The differential cross sections are given by $d\sigma/dt = Ae^{Bt+Ct^2}$, where t is the squared 4-momentum transfer, and A, B, and C are energy dependent coefficients. Typically, B is about 8 GeV^{-2}, and C is small. The angular distribution of the π^+ momentum in the rest frame of the ρ^0 is given by $W(\theta) = \sin^2\theta$, where θ is the angle between the Z axis (taken along the incident photon beam direction) and the π^+ momentum.

We find that the protons from the reactions are concentrated with momenta between approximately 0.25–0.75 GeV/c and at angles $\theta_p < 60\,\text{deg}$. The π^+ angles are not confined, but most of the events occur for angles $\theta_\pi < 50\,\text{deg}$ and with momenta ranging up to and beyond 1.25 GeV/c. Increasing the beam energy increases the momenta of the emerging particles, but does not appreciably alter the distribution in angles.

The effects of the finite resolution and solid angle of the CLAS on the $\pi^+\pi^-p$ final state have also been studied. Two magnetic field settings, the nominal design value and one-half of that value, have been tested. The missing-mass resolution becomes worse by about a factor of $\sqrt{2}$ with the lower field, but the effective solid angle increases by about 15%. This solid angle is about 35% for $\pi^+\pi^-$ detection, about 37% for π^-p detection, and about 40% for π^+p detection. Detection of all three particles reduces the effective solid angle to about 21%. In the case of an undetected π^+ or π^-, the missing-mass resolution is about 14 MeV with the lower field, which is about twice the binning width in the photon tagger. It may be possible to combine events from several of these modes to increase the overall solid angle of detection.

4.3 Count rates

Count rates and beam-time requests may be estimated from the conditions of our experimental setup and the known cross sections for meson photoproduction. We assume the following:

Beam energy:	2.4 GeV
Tagging range:	0.70–2.15 GeV (30–90%)
Photon flux:	10^7 per second (total)
Solid angle:	70% of 4π per charged particle or photon
π^0 conv. prob.:	4% (20% per photon)
Targets:	Liquid H_2 and D_2
Target thickness:	1 gm/cm^2 per nucleon (about 14 cm)

The assumed solid angle is a little larger than that found in our preliminary Monte Carlo simulations of the CLAS response. We believe that some of the differences will be reduced with more refined calculations. At worst, we may overestimate the count rates of ρ^0 production by a factor of about 1.5. With an open trigger of two charged particles in the CLAS, we estimate a total event rate of about 60/sec.

By using the Breit-Wigner expression for cross sections, and integrating the decay probabilities over each resonance, we can estimate the meson production cross sections. Estimates of the event rates for ρ^0 decays are given in Table II. Many of the resonances provide a very large count rate. However, since we also need to distinguish the resonance-production process from the stronger diffractive process, we will need to take data out to large $|t|$ ($|t| > 1$ GeV^2), where the differential cross sections are very small. In order to assure good statistics, we request 100 hours beam time for each of the hydrogen and deuterium targets, for a total of 200 hours in this first part.

The second part of the experiment will involve a simple modification of the CLAS in order to provide detection for π^0's. The trigger will also be suitably adjusted. The total event rate under these conditions is estimated to be less than 1/sec. There are essentially no data on hydrogen and deuterium above $-t = 0.5$ GeV^2. Estimated omega-decay event rates for the baryon resonances in the Isgur-Karl model are listed in Table II. Due to the requirement for π^0 detection, these rates are significantly lower than those for rho decays. We are investigating the possibility that omegas can be identified through the use of missing-mass relationships, assuming suitable detection of recoil protons in the inner vertex detector. If feasible, a large part of our detection efficiency will be regained and omega production rates will be more nearly comparable to those for rhos. Nevertheless, we request 200 hours for each of the hydrogen and deuterium targets, for a total of 400 hours in part 2.

We anticipate that approximately 100 hours will be needed for setup and tuneup of the experimental apparatus. Hence the total beam-time request is 700 hours, or approximately one month.

5 Future Experiments

The experiment proposed here will provide an abundance of data that can serve as the basis for several thesis topics. It is also the first of a series of experiments that will be proposed as CEBAF develops. We will describe several of these briefly.

(1) The most obvious extension of this experiment will invlove the use of polarized photons. Spin observables have always provided the basis for significant constraints on theoretical analyses, for new insights, and frequently for surprises. We expect polarization data to be most valuable in helping to distinguish the multitude of overlapping baryon resonances and mapping out the various decay channels, features not available so easily with pion beams. With its complete azimuthal coverage, the CLAS is an ideal detector for physics with linearly polarized photons.

(2) Another extension will be to higher energies. A number of N^* and Δ resonances, mainly of high spin, are known or identified as possibly existing in the energy range between 2–3 GeV baryon mass.[33] A 4-GeV electron with the tagger will cover the mass range 1800–2750 MeV. Even though the resonance widths are becoming large, and the diffractive mechanisms are increasingly important, the excellent capability of CEBAF may still permit fruitful studies of photoproduction reactions at these higher energies.

(3) Vector meson photoproduction may also be studied on ^{3}H and ^{3,4}He targets as a first step towards the study of such reactions in nuclei. We have not found any data in the literature for these targets, the lightest nuclear target in past studies evidently being ^{9}Be. The mass-3 targets have several favorable attributes. Coherent photoproduction may be compared with detailed predictions from realistic wave functions generated with Faddeev techniques. For quasi-elastic processes, the ^{3}He and ^{3}H targets may be used as substitutes for proton and neutron targets, respectively, thereby augmenting the interpretations of the data from our experiment. All of the targets, especially ^{4}He, may be used to test isospin symmetries.

(4) Once the CLAS detector, the data acquisition, and the analysis techniques are well understood, searches can be made for the production of exotic mesons such as the scalar σ meson (alias ϵ meson) which is sometimes thought to have a mass near 600–700 MeV. The expected principal decay mode of the σ is 2π but, since it is an isoscalar meson, it can be distinguished from ρ decay by looking exclusively at the $\pi^0\pi^0$ channel. Polarization observables might also be useful in projecting σ production from the large background of vector ρ particles. A σN decay channel is identified in the phase-shift analysis of πN

data,[16] and calculated in the papers on the Quark-Pair-Creation model.[2] Evidence for the existence of a distinct σ particle comes and goes over the years. Very recent work on five-pion decay of the J/ψ suggests the presence of a meson resonance near 400–500 MeV that has both $\pi^+\pi^-$ and $\pi^0\pi^0$ decay modes.[35]

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Table 1 : Partial widths for photon and hadronic couplings to baryon resonances in the Isgur-Karl model.[3,4,5] The total hadronic width, summed over all identified channels, is also given. The units are MeV.

Mass	J^π	γp	πN	$\pi\Delta$	ρN	ωN	Total
N(1490)	$1/2^-$	1.3	28.	2.9	40.	0.	98.
N(1655)	$1/2^-$	0.72	76.	67.	102.	1.4	262.
N(1535)	$3/2^-$	0.58	85.	52.	27.	0.	164.
N(1745)	$3/2^-$	0.009	13.	317.	26.	2.9	360.
N(1670)	$5/2^-$	0.013	30.	86.	5.3	0.	130.
N(1405)	$1/2^+$	0.026	46.	5.8	0.1	0.	52.
N(1705)	$1/2^+$	0.23	45.	13.	36.	0.8	108.
N(1890)	$1/2^+$	0.057	19.	12.	22.	37.	96.
N(2055)	$1/2^+$	0.009	1.4	3.2	1.7	32.	39.
N(1710)	$1/2^+$	1.0	42.	4.4	156.	32.	242.
N(1870)	$3/2^+$	0.027	10.	19.	2.3	98.	149.
N(1955)	$3/2^+$	0.021	1.2	88.	56.	90.	236.
N(1980)	$3/2^+$	0.031	1.2	96.	71.	55.	223.
N(2060)	$3/2^+$	0.0001	0.3	31.	15.	98.	145.
N(1715)	$5/2^+$	0.29	50.	4.4	20.	1.4	77.
N(1955)	$5/2^+$	0.24	0.2	64.	67.	184.	324.
N(2025)	$5/2^+$	0.001	1.7	67.	66.	180.	316.
N(1955)	$7/2^+$	0.006	9.6	36.	18.	53.	126.
Δ(1685)	$1/2^-$	0.34	11.	64.	64.		139.
Δ(1685)	$3/2^-$	1.0	24.	146.	289.		459.
Δ(1925)	$1/2^+$	0.0	28.	35.	37.		112.
Δ(1240)	$3/2^+$	0.46	121.	0.	0.		121.
Δ(1780)	$3/2^+$	0.14	29.	74.	32.		139.
Δ(1975)	$3/2^+$	0.030	0.	59.	35.		94.
Δ(1940)	$5/2^+$	0.059	16.	41.	45.		103.
Δ(1975)	$5/2^+$	0.51	1.	41.	388.		430.
Δ(1915)	$7/2^+$	0.27	56.	30.	88.		178.

Table 2 : Count rates in events/hour for decays of N^* and Δ resonances into ρ^0p, ωp, ρ^0n and ωn channels. The values are based on the model of Isgur and Karl.[3,4,5]

Mass	J^π	ρ^0p	ωp	ρ^0n	ωn
N(1490)	$1/2^-$	16,000	0	10,500	0
N(1655)	$1/2^-$	4,950	4	780	1
N(1535)	$3/2^-$	4,950	0	4,950	0
N(1745)	$3/2^-$	20	0	680	4
N(1670)	$5/2^-$	25	0	280	0
N(1405)	$1/2^+$	2	0	1	0
N(1705)	$1/2^+$	1,170	2	230	1
N(1890)	$1/2^+$	130	13	0	0
N(2055)	$1/2^+$	3	3	1	1
N(1710)	$1/2^+$	20,300	250	3,440	42
N(1870)	$3/2^+$	7	22	10	27
N(1955)	$3/2^+$	90	9	515	49
N(1980)	$3/2^+$	170	8	380	18
N(2060)	$3/2^+$	0	0	32	12
N(1715)	$5/2^+$	3,450	14	540	2
N(1955)	$5/2^+$	1,320	210	725	115
N(2025)	$5/2^+$	4	1	790	127
N(1955)	$7/2^+$	33	6	175	30
Δ(1685)	$1/2^-$	5,170			
Δ(1685)	$3/2^-$	42,700			
Δ(1925)	$1/2^+$				
Δ(1240)	$3/2^+$				
Δ(1780)	$3/2^+$	1,690			
Δ(1975)	$3/2^+$	380			
Δ(1940)	$5/2^+$	1,415			
Δ(1975)	$5/2^+$	23,600			
Δ(1915)	$7/2^+$	10,200			

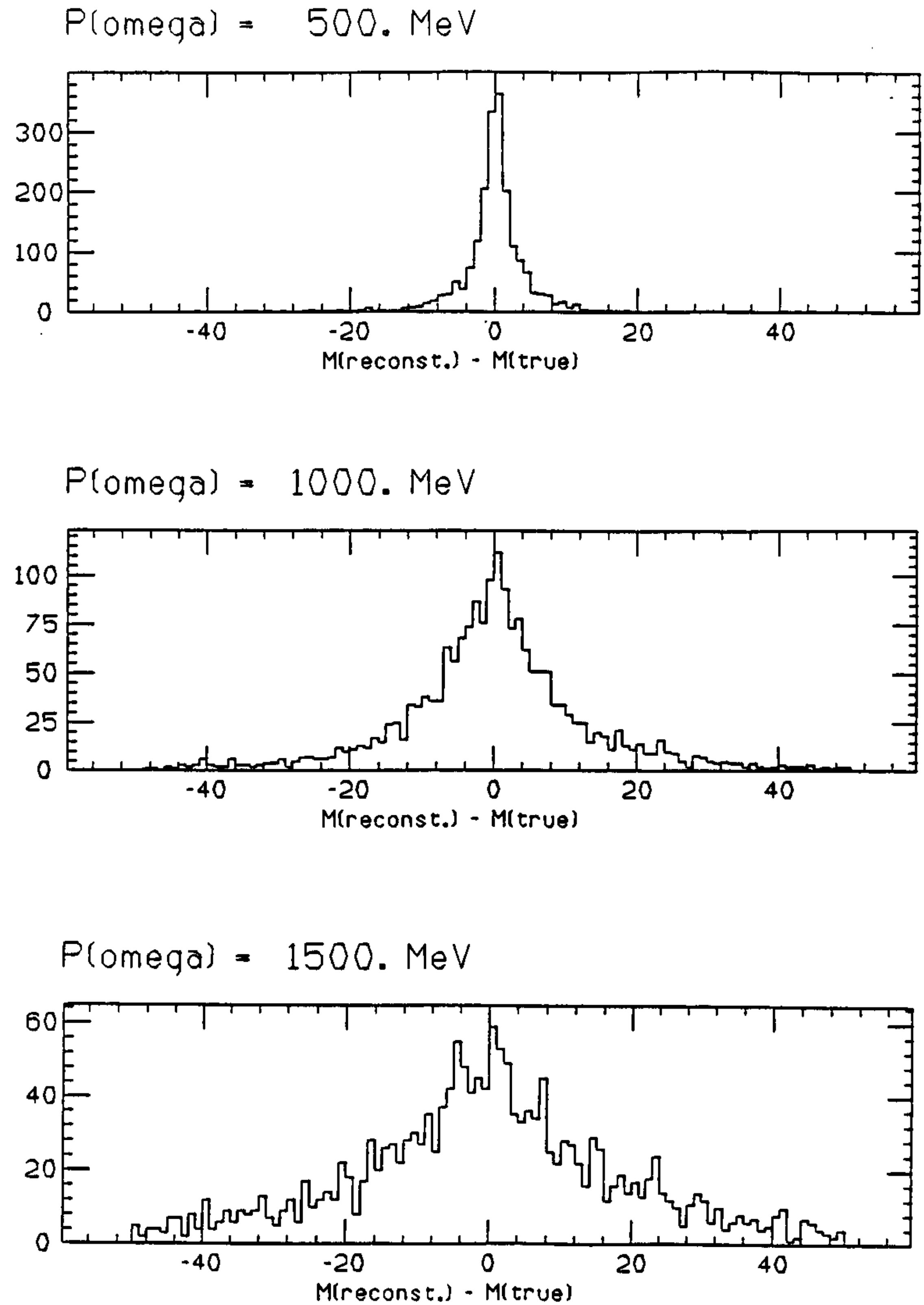

Figure 3: Resolution of the ω mass as reconstructed from the detection of the decay products, for ω momenta of 500, 1000, and 1500 MeV/c.

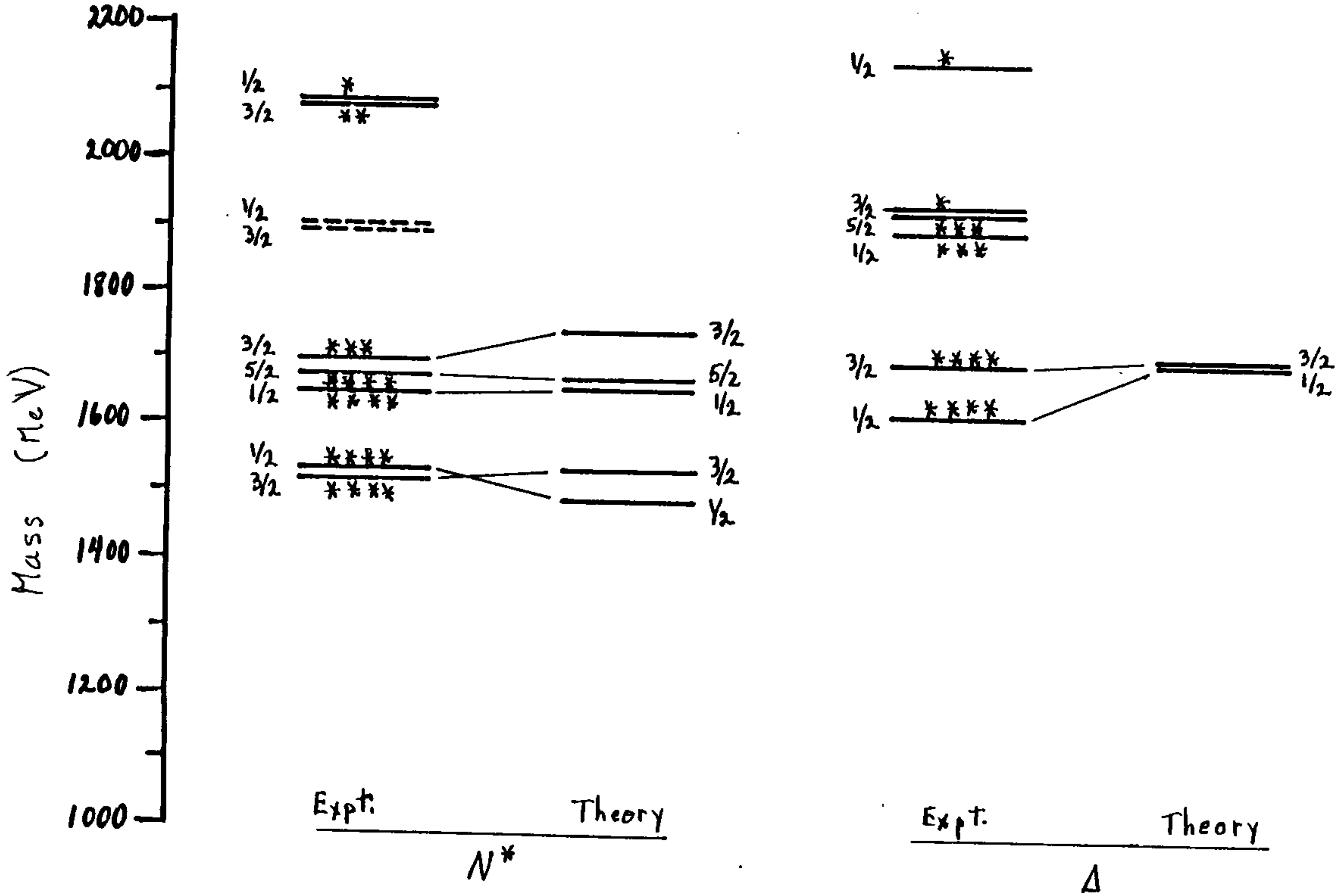

Figure 1: Empirical and theoretical spectra for negative-parity N^* and Δ resonances. The empirical spectra are taken from the Particle Data Group (Ref. [33]), but augmented with possible resonances from the VPI phase-shift analysis (Ref. [16]), shown as dashed lines. The theoretical spectra are those of Isgur and Karl, Ref. [3].

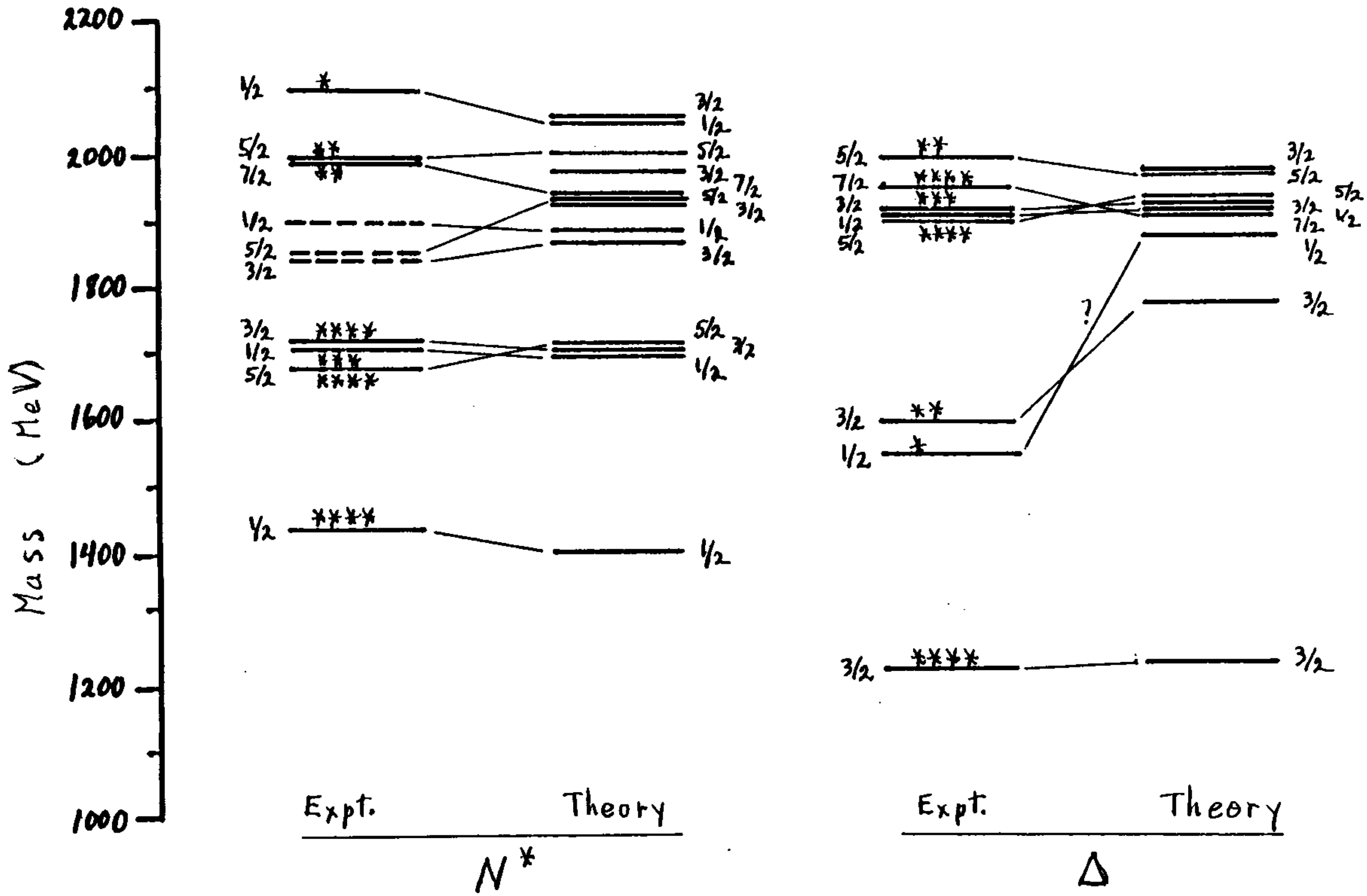

Figure 2: Empirical and theoretical spectra for positive-parity N^* and Δ resonances. The empirical spectra are taken from the Particle Data Group (Ref. [33]), but augmented with possible resonances from the VPI phase-shift analysis (Ref. [16]), shown as dashed lines. The theoretical spectra are those of Isgur and Karl, Ref. [3].